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Polarized heavy ion sources

Jahan Singh
Department of Physics, Maharshi Dayanand University,
Rohtak, India

Abstract : A review of the basic principles, status and methods for the production of polarized heavy ions is presented. It is shown that the schemes for many kinds of polarized heavy ions exist The prospects for further improvements and development of many types of polarized heavy ions are encouraging.

Keywords : Polarized heavy ions, production, review

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1. Introduction

Normally in a target or in a beam, the spin axes of the nuclei point in all directions and randomly. These nuclei are called "Unpolarized" assemblies. Many elegent experiments can be devised and new effects are observed if the spin axes of the nuclei are made parallel to a certain direction called as the quantization axis. If we consider nuclei of having spin 'I' which are placed in an external magnetic field than the nuclei can be in any one of $(2I + 1)$ "orientation states" which are characterized by the magnetic qunatum numbers 'm'. If all the orientation states have the same "Occupational number" then the nuclear system is called unpolarized assembly. On the other hand if the occupation number for the different states are unequal, the system is called "oriented assembly" as shown in Figure 1. The polarized systems are of two types :

(a) Vector polarized assembly

When the occupation number for the positive and negative values of the same magnetic quantum number are unequal than the system is called "Vector Polarized". The degree of polarization is defined by a parameter :

$$P = \varepsilon m. N_m / I.\varepsilon N_m \tag{1}$$

where N_m is the population of orientation states for magnetic quantum number "m". For the disoriented assembly, the population of states for $+m$ and $-m$ are equal, *i.e.*, $N_m = N_{-m}$ and $P = 0.0$. For the polarized assembly $N_m \neq N_{-m}$ and there are possibilities :

(i) Either $N_m = 0$ or $N_{-m} = 0$. This gives $P = -1.0$ or $+1.0$ because $\varepsilon N_m = 1$.

(ii) There is mixture of N_m and N_{-m}. Then P lies between +1 and −1, *i.e.*, $1 > P > -1$.

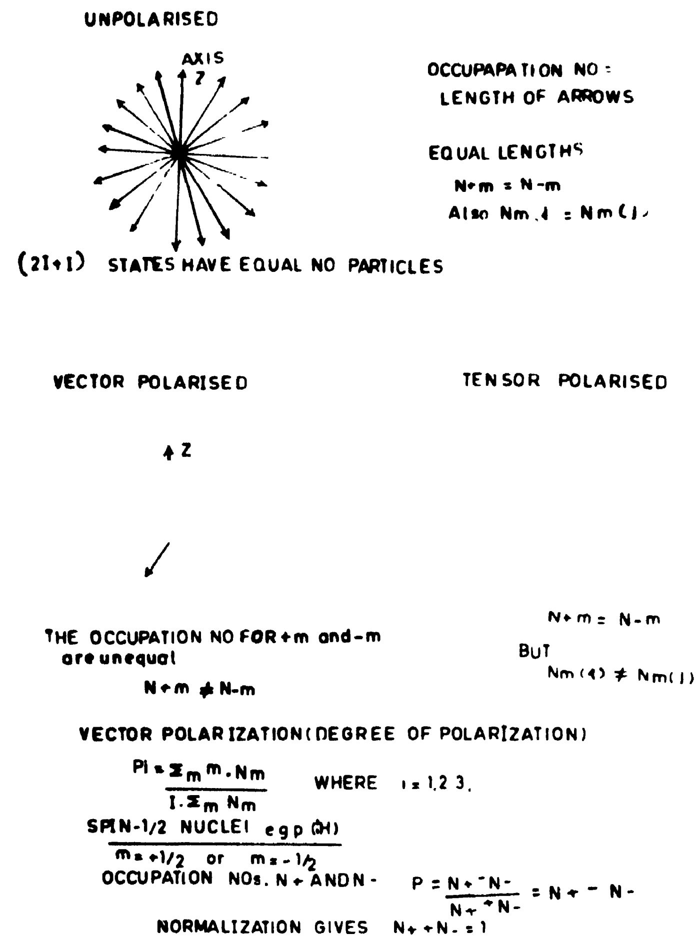

Figure 1. Representation of unpolarized, vector and tensor polarized nuclei.

(b) Tensor polarized assembly (aligned assembly)

If the nuclei are oriented along the quantization axis such that $N_m = N_{-m}$ but N_m $(i) \neq N_m$ (j) where 'i' and 'j' denote the indices for the different quantum numbers of the spin operator. There are more nuclei in one direction than the other. For such systems the degree of orientation (alignment) called "Tenson Polarization" is defined by the parameter,

$$P_{ij} = 3\left[\varepsilon N_m\left\{m^2 - I(I+1)/3\right\}/I^2.\varepsilon N_m\right] \quad (2)$$

It should be noted that $P_{ij} = 0$ for the system having the spin less than one. In terms of the above parameters P and P_{ij} we have the following systems :

(i) $P = 0 \doteq P_{ij}$ for a disoriented assembly.

(ii) $P \neq 0$ but $P_{ij} = 0$ for pure vector polarized assembly.

(iii) $P \neq 0$ and $P_{ij} \neq 0$ for mixed vector and tensor assembly.

(iv) $P = 0$ but $P_{ij} \neq 0$ for a pure tensor assembly.

2. Polarized heavy ion sources

A very interesting field in ion technology is the development of polarized heavy ion sources. A selected list of heavy ions which possibly could be polarized by the atomic beam method using surface ionization is given in the Table 1. The polarized heavy ions are very much interesting in nuclear physics due to the under mentioned reasons :

(i) that the spin-dependent part in the nuclear interaction can be investigated with polarized ions;

(ii) for ions with $I > 1$ having the static ground state defermation a "shape effect" appears due to the projectile shape. This effect would be more dominant for aligned deformed heavy ions;

(iii) in a spin aligned beam the quadrupole moments of the mass and charge distribution are also aligned. The use of spin processor after ion source can give any desired direction in the spin axis. Hence the symmetry axis of the mass and charged distribution could be changed;

(iv) the heavy ion interaction is very sensitive to the interaction distance. Using aligned deformed heavy ions, this critical distance can be changed just by turning the alignment axis;

(v) the ^{7}Li and ^{23}Na ions have strong deviations from spherical shape as seen from Table 2. Hence, they are the most interesting to study shape effects.

Due to above reasons, the polarized heavy ion sources have been developed at six laboratories [1–6] as mentioned in Table 3. We summarize the main features of these sources. The basic configuration of the source is shown in Figure 2. A polarized atomic beam is produced by an oven, a Stern-Gerlach magnet and a system of *hf* transitions and this is ionized to positive ions on a hot tungsten surface.

The ionizer is operated in the transverse guide field of a dipole magnet. The beam is extracted upward and focussed by 90° spherical electrostatic deflector into the charge exchange canal. The negative ions beam is then passed through a Wien filter, where the desired spin direction is set, and injected into the preaccelerator tube;

Table 1. List of heavy ions which can be produced by the atomic beam method and surface ionization

Element Z	Isotope	Abundance %	Ionization energy (eV)	Electron affinity (eV)	Nuclear spin	B_{crit} (mT)	Surface	Ionization efficiency (max. %)	Charge of ion
Electronic structure : 2 S 1/2, electronic spin 1/2									
3	6Li	7	5.4	0.61	1	8 2	W–O	100	+
	7Li	93	5 4	0.61	3/2	28 8	W–O	100	+
11	23Na	100	5.1	0.54	3/2	63 3	W–O	100	+
	39K	93	4.3	0.50	3/2	16 5	W–O	100	+
19	41K	7	4.3	0.50	3/2	9 1	W–O	100	+
37	85Rb	100	4 2	0 49	5/2	10.8	—	—	+
55	133Cs	100	3.9	0.47	7/2	328	W–O	100	+
Electronic structure 2 P 1/2, electronic spin 1/2									
49	113In	4	5 8	70	9/2	12019	Ir/W–O	40/90	+
	115In	96	5 8	3.5	9/2	12021	Ir/W–O	40/90	+
Electronic structure 2 D 3/2, electronic spin 3/2									
71	125Lu	97	5.4		7/2	56 5			+
Electronic structure 2 P 3/2, electronic spin 3/2									
9	19F	100	17.4	4 1	1/2	71.7			-
	35Cl	75	13.8	3.8	3/2	21 0	W–Th/W–O–Ca	2.6/50	-
17	37Cl	25	13.0	3.8	3/2	17.5	W–Th/W–O–Ca	2.6/50	-
35	79Br	50	11.8	3.6	3/2	102	W–Th	0.4	-
	81Br	50	11.8	3 6	3/2	108	W–Th	0.4	-
53	127I	100	10.5	3 1	5/2	124	W–Th	0.3	-

A schematic diagram of the Heidelberg-Dersbury polarized heavy ion source is shown in Figure 3. The description of basic units is given below;

Table 2. List of polarized heavy ion beams.

Nucleus	I^{π}	$B_{crit}^{(mT)}$	$f = gA/2$	Q/ZeR^2
^{6}Li		8.2	2 5	0.00
^{7}Li	$\frac{3}{2}^{-}$	28.8	7 6	– 0.23
^{23}Na	$\frac{3}{2}^{+}$	63.3	17.0	0 15
^{39}K	$\frac{3}{2}^{+}$	16.5	5.1	0 03
^{133}Cs	$\frac{7}{2}^{+}$	328	49 0	0 00
^{19}F	$\frac{1}{2}^{+}$	71.7	50 0	-
^{35}Cl	$\frac{3}{2}^{+}$	21.0	9.6	– 0.04
$^{79(81)}Br$	$\frac{3}{2}^{-}$	102(108)	55.5(61.3)	0 05(0 04)
^{127}I	$\frac{5}{2}^{+}$	124	71.3	– 0.06
^{115}In	$\frac{9}{2}^{+}$	12021	70.7	0.08

Here Q/ZeR^2 is a measure of the deviation from spherical shape and f is the ratio of spin precession angle and deflection angle in a magnetic field for singly charged ions

Table 3. List of polarized heavy ion sources

Sr. No	Laboratory	Polarized Ions	Polarizer	Charging system
1.	MPI Kernphysik Heidelberg (EN Tandem)	^{6}Li and ^{7}Li	Multiple magnet	Surface ionizer, charge exchange
2	MPI Kernphysik Heidelberg	^{6}Li, ^{7}Li and ^{23}Na	Optical pumping, multiple magnet	Surface ionizer, charge exchange
3	NSF Daresbury	^{6}Li, ^{7}Li and ^{23}Na	Multipole magnet	Surface ionizer, charge exchange
4	Florida State University Tallahassee	^{6}Li and ^{7}Li	Optical pumping	Surface ionizer, charge exchange
5.	University of Madison Wiscousin	^{6}Li	Multipole magnet	Direct charge exchange to negative ions
6.	Laboratoire National SATURNE	^{6}Li	Multipole magnet	Surface ionizer

2.1. *The sodium oven*

The sodium oven consists of an evaporation cylinder and a collimator chamber and is of the recirculating type. Two heater cartridges in a copper jacket keep the cylinder temperature at

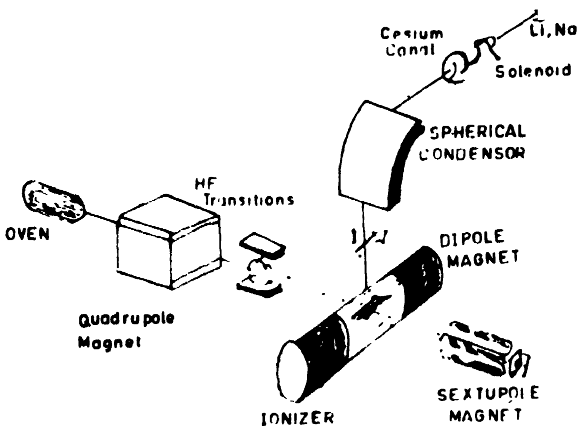

Figure 2. Configuration of polarized heavy ion source

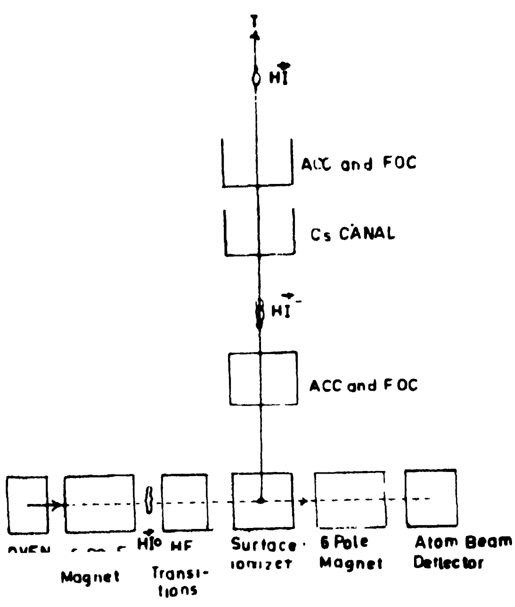

Figure 3. Schematic diagram of polarized heavy ion source.

500°C while the collimator temperature is maintained around 140°C which allows the Na vapour to condense and the liquid to be directed back into the cylinder. The atomic beam is formed by 1.5 mm holes in the cylinder. The collimater beam has a density upto 7×10^{17} particles/S. Sr as measured by a small ionizer directly behind the oven gate. The oven is filled with sodium and serviced in a glove box which has inert argon atmosphere.

2.2. *Stern-Gerlach separation magnet*

For the Stern-Gerlach separation a quadrupole magnet is chosen. The magnet length is 38 cm. The pole tips, pole pieces and the yoke of the magnet are manufactured from Armico iron. The gap between the pole tips is 11 mm and the shape of the pole tips is optimized to obtain the maximum field strength (23.5 KG) in the gap. The coils (each of 26 turns) are made from copper tube (I.D. = 4 mm and O.D. ≐ 6 mm) insulated by fiberglass and impregnated with Araldite. The magnetic field at the pole tips saturates around 16 KG at = 180 A. The total power consumption is 1.5 KW and the pressure in the magnet chamber is of the order of 10^{-7} torr.

2.3. *The rf transitions*

The *rf* transitions units are installed around a glass tube (30 cm long and 14 mm inside diameter) connecting the quadrupole magnet and the ionizer vessel. The weak field transition (WFT) produces the vector polarization at = 10 MH_z whilst the strong field transition (SFT) produce the tensor polarization at = 2GH_z. In both cases the oscillator signal is amplified in externally controlled power amplifiers before being fed into the resonators. Two transitions between 4 ⟶ 6 and 2⟶ 8 levels on the Breit-Rabi diagram (Figure 4) are employed in SFT. The setting of both the gradient and static magnetic fields

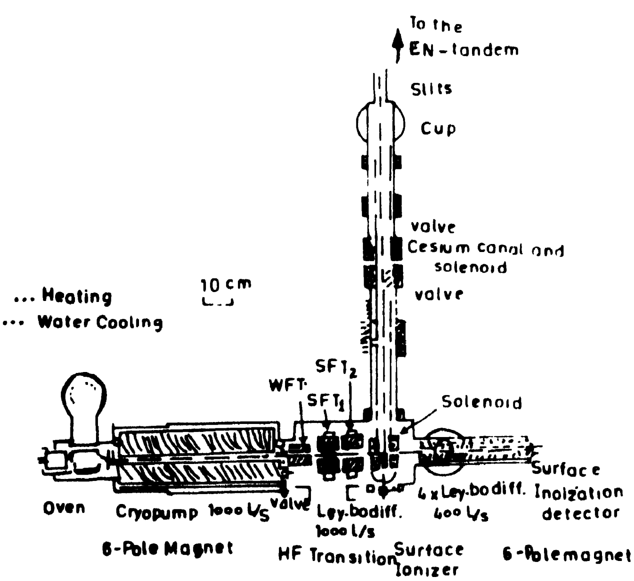

Figure 4. Polarized heavy ion source in detail.

in the transition region is checked by observing if there is about 25% decrease in the current monitered in the smell ionizer sited along with the atomic beam line behind the sextupole magnet.

2.4. The ionizer assembly

The atomic beam is ionized on a tungston strip (10 mm) wide and 50 μm thick) which is tilted at 45° to the beam axis. It is heated by an ac current of more than 50 A to about 1800 K. The ionizer is operated at + 4KV for lithium and +12 to 16 KV for sodium to obtain the optimum energy for the charge exchange in cesium vapour. A dipole magnet with 10 cm diameter pole tips and 12 cm gap provided a strong magnetic field to define the spin symmetry axis during ionisation. The ionizer filament (strip) can be remotely moved out of the atomic beam path when setting the *rf* transitions. The strip temperature is deduced by pyrometer. The positive ions are extracted from the surface of strip by a grid (90% transperancy). Then the positive beam is deflected and focused into the exchange canal by a spherical condenser of mean radius 20 cm and 4 cm gap. The electrodes are manufactured from cast red brass rings and hard chromium plated. The deflection voltages of ± 1 to ± 2 KeV are used. A Faraday cup is inserted at the object point of the condenser to optimise the setting of the extraction system.

2.5. The charge exchange unit

The extracted beam from the ionizer is brought into the axis of the injection by a 90° spherical condenser which has a focus in the middle of the 18 cm long and 10 mm diameter canal of the charge-exchange unit. The canal is of the wick type and is mounted in the bore of a soelenoid which produces a guiding field of 1.5 KG along the direction of the beam. About 5 g of cesium, transported in the liquid state by argon pressure from a heated external reservoir, is kept in the cannal central cavity. The canal is heated to 140 to 150°C for an optimum yield of the negative fraction. The canal ends are kept at 35°C to condense the Cs vapours. The resulting liquid Cs is fed back to the canal centre by the capillary action of a fine mesh lining the walls. Cooled copper plates around the canal ends prevent the excape of Cs from the unit. The Cs vapour density is monitored by small ionizer behind the spherical condenser. The charge exchange unit is electrically insulated allowing the canal to be operated at a potential upto 6 KV. The effective charge-exchange (the ratio of the negative and positive currentsa) at E = 18 KeV is about 3%.

2.6. The Wien Filter (W. F. assembly)

The Wien Filter is used to process the spin from the original direction parallel to the beam axis into any desired direction. The Wien Filter is rotatable around the beam axis. It has a magnet of 38 cm long with a 5 cm gap. The electrodes are mounted in a rectangular vacuum pipe. The optimum transmission through the Wien Filter is checked by inserting a third Faraday Cup. The asymmetry in the photon counting rate of circularly polarized light depends on the angle between the spin symmetry vector rotating in the WF magnetic field and the direction of photon emission as

$$\varepsilon_c = T_{10}t_{10} \cos\phi + T_{20}t_{20} (3 \cos^2\phi - 1)$$

For Daresbury source the beam intensities upto 40 μA have been measured in first Faraday Cup *i.e.* after the ionizer. The maximum vector polarization is close to the theoretical value of $t_{10} = 0.67$

3. Measurement with polarized heavy ion beams

There are, in general, two types of polarization measurements. Firstly, the polarization measurements in which initially unpolarized beam is scattered from the target under investigation and polarization produced is subsequently analysed by a target of known polarization efficiency. Secondly, the asymmetry measurement in which the polarized beam is used to measure asymmetries in the scattering from the target in question. These two

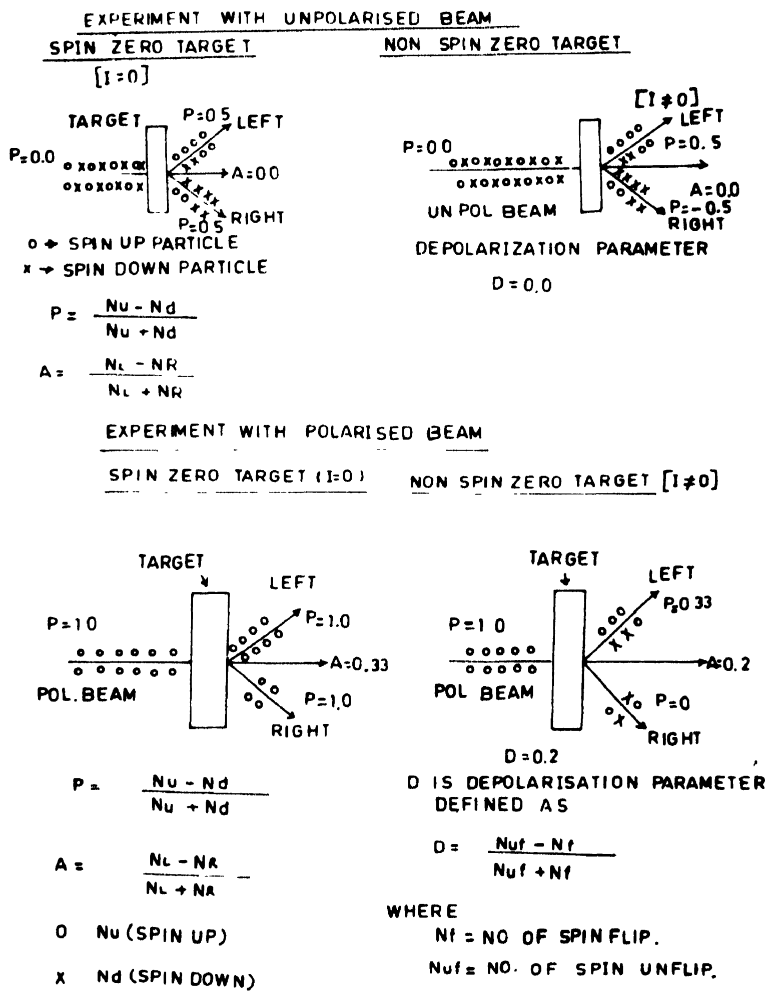

Figure 5. Experiments with polarized heavy ion beams.

quantities are identical for elastic scattering due to the invariance of the scattering. The measurements are shown in Figure 5 and are summerised below :

(i) When an unpolarized beam is incident on the target then equal number of the nuclei are scattered to the left and right sides but each side has a different number of the spin up and spin down nuclei, the scattered beam is polarized *i.e.* target acts as a polarizer, we define the polarizing power as :

$$P = \left(N_u - N_d\right) / \left(N_u + N_d\right) \tag{3}$$

where N_u and N_d are the number of the nuclei with spin up and spin down in the same side.

(ii) If a completely polarized beam is scattered by the spin zero target them more nuclei are scattered to the left or right side depending upon the direction of beam polarization. We measure the asymmetry parameter (called the analyzing power) defined as :

$$A = \left(N_L - N_R\right) / \left(N_L + N_R\right) \tag{4}$$

where N_L and N_R are the numbers of nuclei scattered to the left and right sides respectively. Hence, the target acts as analyzer.

(iii) When the polarized beam is scattered with the target having non-zero spin, then it is pcssible for a nucleus with spin in one direction to have its spin flipped into the opposite direction in the scattering process. The change in angular momentum due to the spin flip can be taken up by the target nucleus if it has a spin. The probability of the spin flip is defined by a depolarization parameter :

$$D = \left(N_{uf} - N_f\right) / \left(N_{uf} + N_f\right) \tag{5}$$

where N_{uf} and N_f are the number of the scattered nuclei without and with spin flip to either side respectively. The depolarization parameter can be used to study the spin behaviour of the target nucleus.

(iv) In this method the unknown forms the first target and the scattered beam is analysed at a second scattering. The asymmetry produced at the second scattering is given in terms of the numbers of the nuclei scattered to the left and to the right as :

$$A = \left(N_{RR} - N_{RL}\right)/\left(N_{RR} + N_{RL}\right) \text{ or } A = \left(N_{LL} - N_{LR}\right)/\left(N_{LL} + N_{LR}\right) \tag{6}$$

depending on whether the first scattering is to the left or to the right of the incident beam. If the two scatterings are coplanar then the asymmetry can be written as :

$$A = P_1 . P_2 \tag{7}$$

where P_1 and P_2 are the polarization produced at the first and second scattering respectively. Experimentally, the asymmetry is determined by eq. (6) and from the known value or P_2, the P_1 is calculated using eq. (7). The nuclear physics with polarized heavy ions has been reviewed by Fick *et al* [7] in Physics Reports.

4. Conclusion

On the basis of present investigations with PHIS it is concluded as under :

(1) The successful operation of the PHIS has shown that the techniques involved are now reliable enough for routine applications in heavy ion reactions. Therefore, an increasing attention is being paid by numerous laboratories to the development of PHIS and nuclear reactions with polarized H.I. beams and targets.

(2) The polarization effects are dominated by quadrupole forces. The VAPs are dominated by an effective spin-orbit potential generated by the quadrupole coupling to the excited levels of projectile. TAPs are manifestations of the Q-momenta.

(3) It is seen that there is a possibility of different types of polarized heavy ion sources. The prospects for further improvements for all types of polarized heavy ion sources are encouraging. It seems entirely likely that in the not-too-distant future nuclear physicists will have the opportunity of working with polarized heavy ion beams of intensity comparable to that of unpolarized beams.

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